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## Fractography, a powerful tool for identifying and understanding fatigue in composite materials

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### Abstract

Fractography is a tool widely used in the academic world but a little-known technique in the industrial world. This tool can be useful at most stages of the development of composite parts: prototyping characterization, industrialization, production quality problems,... Finally when a composite part is broken during service, fractographic analysis is one of the most efficient tools for the determination of the root causes of failure. Fractography is useful for the engineer who has to determine if the failure results of a mechanical overload or of a fatigue phenomenon.

The implementation of a fractographic investigation requires to follow a methodology with different steps:

The first step is to determine the direction of propagation in the different zones of the rupture by recognition of features on the broken surface. From these results, the initiation area can often be identified. Then a long part of the work consists in seeking features of static or fatigue damage. Fractography also allows to determine what type of mechanical loading has caused the micro-damage in the initiation area. This information can be compared with the expected loading.

Sometimes, the fatigue fractographic features are localized just along manufacturing defects. In this case, a specific study is required to establish the harmfulness of these defects. The defect acceptance criteria after manufacturing are then sometimes amended.

Article will discuss these aspects through industrial examples.

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## 1. Introduction

This article illustrates the importance of fractography to characterize fatigue phenomena in polymer composite materials. Over the last thirty years, the increasing uptake of composite materials in many industries has led to a significant rise in the need to consider fatigue in design. Although criteria for fatigue design are still the subject of numerous studies [1, 2, 3], failures in-service due to non-conservative fatigue design are extremely rare. This is perhaps testament to the inherent resistance of fibre reinforced composites to fatigue damage growth. However, based on the experience of the authors, there are a number of instances where composite components have failed prematurely under fatigue loading when combined with other factors such as manufacturing defects, environmental conditions, unanticipated mechanical loading, etc. Following an overview of fractographic methodologies for polymer composites, and an overview of features associated with fatigue, this article presents examples of in-service failures in which fractographic analysis has been utilized.

## 2. Methodology of fractography

The methodology for fractographic analysis entails two main steps: *macroscopic* and *microscopic* observations. The *macroscopic* approach is often necessary to identify the main directions of crack propagation, and can be used to identify the local area in which initiation has occurred. The *microscopic* approach allows to confirm the directions of propagation gleaned from the *macroscopic* approach but this usually must be achieved by dissecting the component. In composite materials, most of the features that permit identification of the direction of crack propagation can only be resolved using scanning electronic microscopy. When the initiation area has been identified with good confidence, the microscopic observation can give information about the root causes of failure such as:

- Tensile or compression loading;
- Mode I or mode II propagation;
- Static or fatigue loading;
- Presence of manufacturing defects;
- Sign of environmental degradation.

When fatigue loading is suspected, the macroscopic approach is very important to assume the location of the initiation site. The zone containing fatigue features is usually very small (a few square millimeters). Scanning electron microscope examination is especially time consuming and it would be impossible to seek fatigue features on the whole broken surface (sometimes the order of square metres).

## 3. Fatigue damage evolution in composite materials

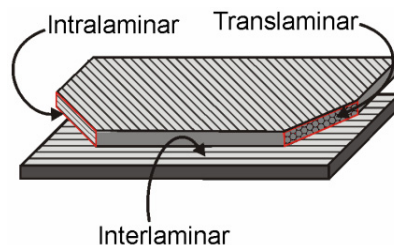


Figure 1 Three different types of fracture mode in laminated composites [4].

Before describing fatigue phenomena in composite materials, the general damage development is presented. As shown in Figure 1, the different failure modes can be partitioned into translaminar (through the thickness, breaking

fibres), intralaminar (through the thickness, splitting between fibres) and interlaminar (delamination between the layers). The different stages in the damage process described below occur earlier or later depending on the type and direction of the reinforcement and also depending on the type of mechanical stresses applied. However, the damage process is always driven by the same process: the first damage occurring requires low energy consumption (interface or matrix failure), while the last stages (fibre breakage) require more significant energy level.

The first step of damage begins logically in zones of lower strength such as the fibre/matrix interfaces and within the matrix itself, with failure over small distances as intralaminar cracks (see Figure 2). Intralaminar damages mainly appear in the areas where fibres are not oriented in the loading axis, when the strain in the matrix exceeds its breaking strain. In general intralaminar cracks are parallel and regularly spaced. A crack density which increases with the applied strain can then be measured. This type of damage has little direct impact on the ultimate strength of the material. In the case of a laminated composites, in addition to the intralaminar damage, interlaminar damage or delamination occurs (see Figure 3). When cracks develop in a ply, the propagation is stopped by the adjacent plies. At the intralaminar crack tip, the singularities of stress make the cracks propagate at the interface between two adjacent plies layers. In the case of a laminated composite with different directions plies, delamination can also initiate because of differences of stiffness of these different plies. This damage can also develop from sources such as manufacturing defects and impact events. Finally, when the density of the matrix damage reaches a certain level, the final stage of damage corresponds to the failure of the fibres, i.e. translaminar failure. This type of damage is mainly involved in the final stages of failure in areas where the fibre orientation more or less coincides with the axis of stress, such as at stress concentrations. The SEM observations in Figure 4 summarise the three main failure modes:

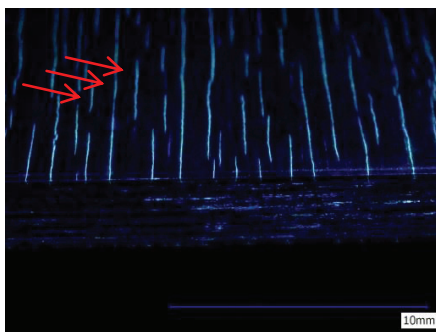


Figure 2 Penetrant inspection showing a large density of intralaminar cracks

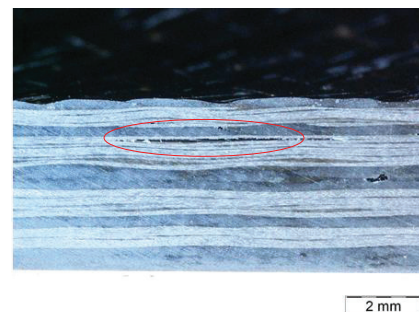
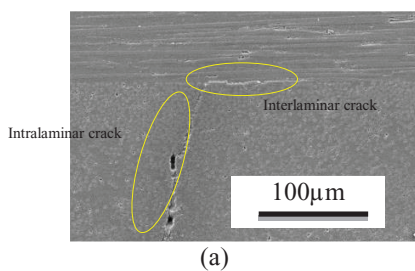
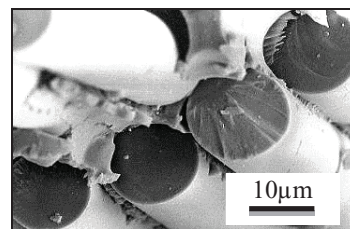


Figure 3 Illustration of delamination during tensile test due to the differences of stiffness of plies



(a)



(b)

Figure 4 (a) interlaminar failure and intralaminar failure; (b) translaminar failure

The matrix damage (intra and interlaminar failures) under mode I (opening mode) form characteristic morphology like riverlines (see Figure 5) or other events. Under mode II (shearing mode) the matrix damage grows forming cusps and scallops resulting from the coalescence of evenly spaced cracks, initially at an angle of  $45^\circ$  relative to the laminate plane (see Figure 5). The morphology of these cusps provides information about the quality of fibre/matrix interface.

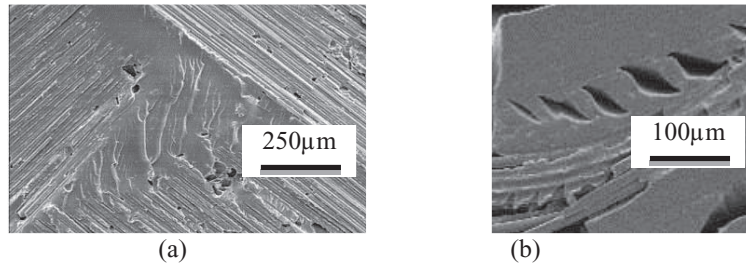


Figure 5 (a) rivers, (b): formation of cusps

The fibers subjected to compression break due to geometric instability. The localized damage grows with shear failure and step region of microbuckling as shown in Figure 6 on thermoset composite (TSC). The individual fibers then fail through bending (tension on one side, compression on other). With thermoplastic composites (TPC), the fibers may fragment in the failure zone as a result of the high compliance of the matrix (see Figure 6). This unstable damage mechanism makes the composites significantly weaker in compression than under tension loading.

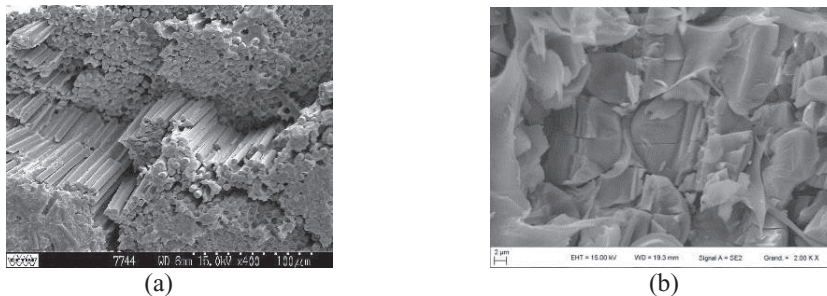


Figure 6 Compression failure: (a) TSC Shear bands, (b) TPC fibre failure

#### 4. Damage specific to fatigue in composite materials

At a mesoscopic scale, the type and the order of occurrence of the damage mechanisms resulting from monotonic or fatigue loadings are fairly similar. The most significant differences in morphology are observable at the microscopic level (striations, rollers, etc). Most of the time, in service, fatigue failure presents unusually large and smooth translaminar failures (in comparison with static failure). Investigations usually help to explain the root cause(s) that are often manufacturing defects or overloads associated with poor design. Furthermore, in the case of glass fiber reinforced composites, chemical attack can also be observed.

##### 4.1. Fatigue features in the matrix

As mentioned previously, the two first steps of damage development are fracture of the fibre/matrix interfaces and then cohesive fracture within the matrix. These two types of fracture can present fatigue striations as shown in Figure 7 and Figure 8. Striations are often highly localized and can be difficult to find. Whilst in the case of metallic



materials it is possible to estimate the number of fatigue cycles by counting the number of striations (measuring the inter-striation distance), this interpretation is not possible on composite materials.

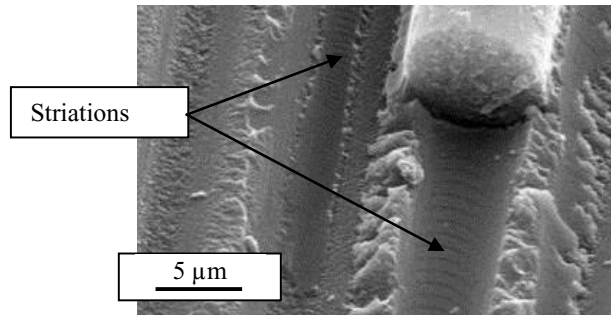


Figure 7 Fatigue striations in fibre imprint region IM7/8552 (Mode I) x5000

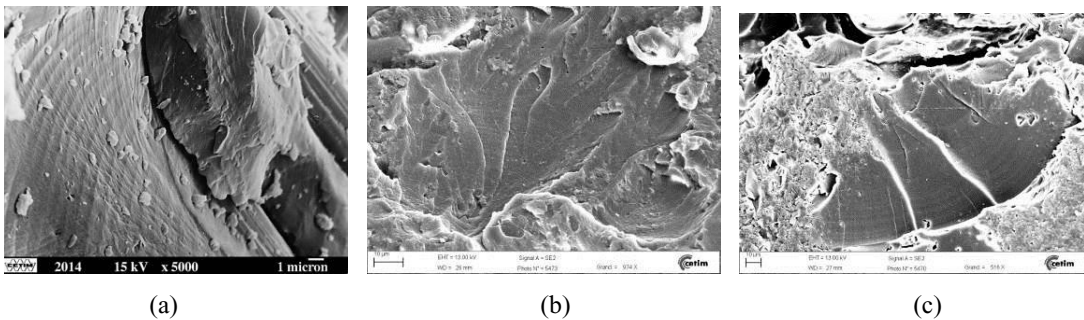


Figure 8 Fatigue matrix striation (a) carbon/epoxy industrial part; (b) and (c) glass/epoxy aeronautical blade

Mode II fracture (in-plane shear) exhibits cusps. Undermonotonic fracture, cusps are sharp and regularly spaced (Figure 9(a)). Under mode II fatigue fracture, cusps appear to have deteriorated and morphology known as “matrix rollers” are prevalent (Figure 9(b)) [17].

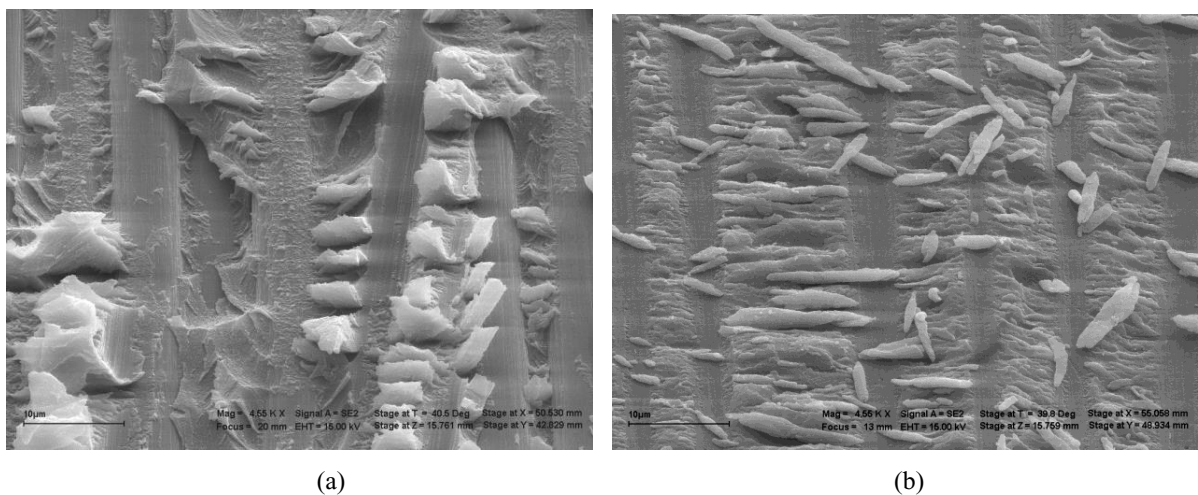


Figure 9 Mode II ruptures (a) monotonic; (b) fatigue

#### 4.2. Fatigue features in the fibres

Glass fibre reinforced composites are weaker under fatigue loading than carbon fibre reinforced composites, since the toughness of the fibre/matrix interface is lower in the former. Moreover, the glass fibres present a specific type of fracture morphology under fatigue loading. At the initiation site the glass fibres present fracture at a single plane and the individual fibres ends present smooth surfaces. These two fatigue characteristics are distinctly different from the usual monotonic features, as illustrated in Figure 10 which are examples of fatigue and static fractures on aeronautical thermoset composite components which have failed in-service.

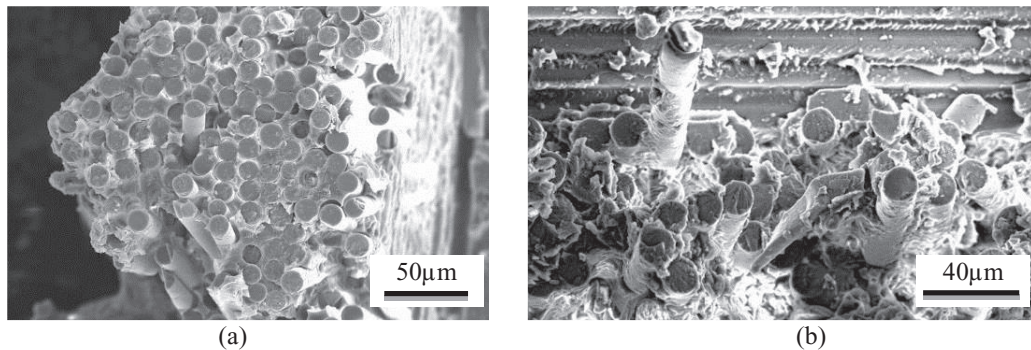


Figure 10 Tensile failure of an aeronautical glass/epoxy composite component: (a): fatigue initiation area one single plane of fracture for many glass fibers and smooth individual fracture surfaces; (b): typical monotonic tensile features on a glass fibre fracture surface.

This phenomenon has also been observed in thermoplastic/short glass fibre composites. Under cyclic tensile stress, glass fibres at different orientations sometimes break cohesively at a single plane and present smooth and flat individual fractures. This morphology is never observed under static loading. Figure 11 and Figure 12 illustrate the process by which the fibres break under fatigue loading. This suggests that under fatigue, for this material, the internal (cohesive) strength of glass fiber is lower than that of the fibre/matrix interface.

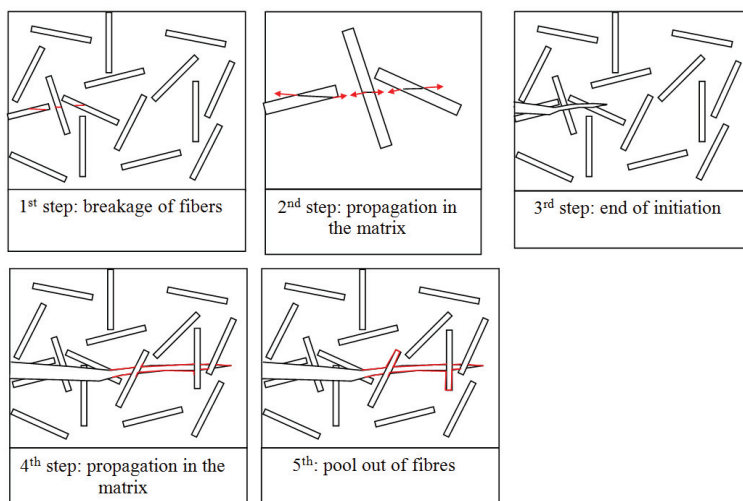


Figure 11 steps of fatigue initiation in a short glass fibres/PA66

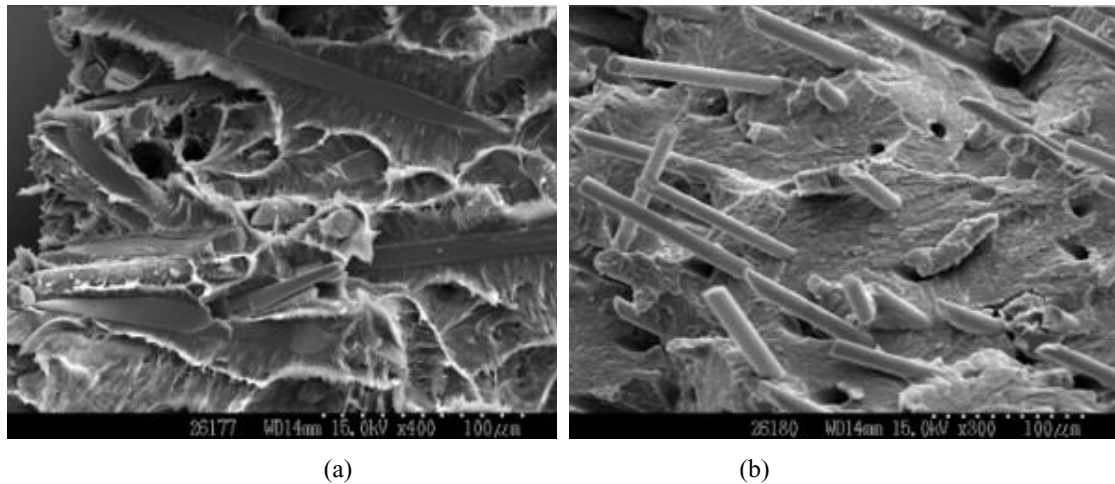


Figure 12 (a) fatigue initiation site (2nd step); (b): monotonic propagation fracture (5th step).

## 5. In service fracture case study

### 5.1. Glass/epoxy part rupture

The study described here presents failure of a glass/epoxy component, fabricated from unidirectional glass fibre and fabric reinforcement under tensile loading. There were no environmental stresses applied to the part. The location of the initiation site was easily found where the opening of the crack was more pronounced. Scanning electron microscopy of the initiation area was undertaken, with a very smooth surface observed at this site, as shown in Figure 13. Such smoothness is often the sign of wearing due to friction between broken surfaces under cycling loading. Observation at higher magnification showed a high degree of fibre and matrix debris (see Figure 13). Finally fatigue striations were observed in the matrix at several locations (see Figure 13). Examination of this failed part showed that the loading at the origin of the failure was cyclic.

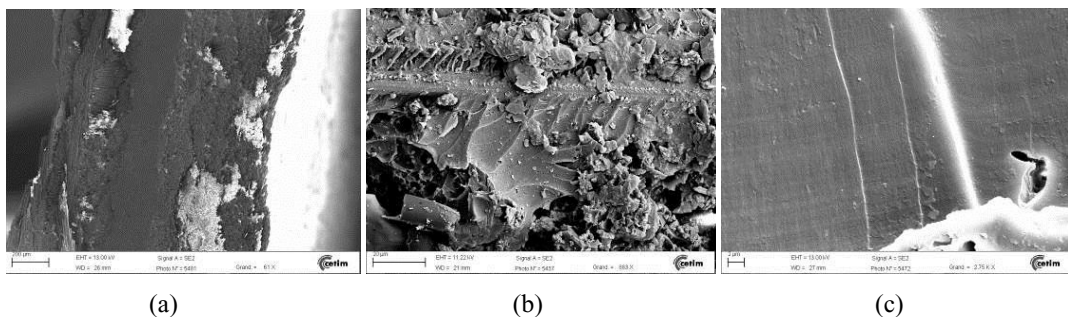


Figure 13 (a): smooth surface due to wear; (b): matrix and fibre debris; (c): striation in the matrix

At sites where fatigue morphology was found, several manufacturing defects were identified. This example is a good illustration of what is often observed in organic composite materials: one manufacturing defect leads to secondary defects around it. In this instance, as shown on Figure 14(a), the main defect is waviness of glass fibre fabric. Over this entire waviness region, there was matrix rich zones and porosity Figure 14(b).



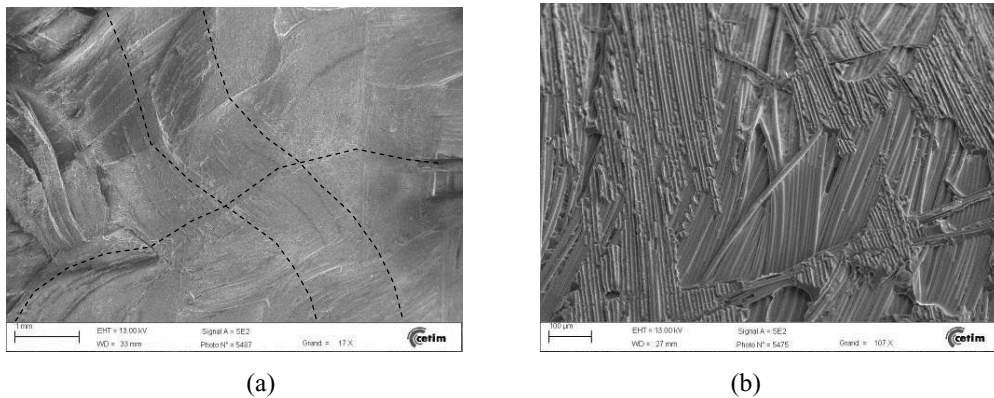


Figure 14 (a): waviness of the glass fibre fabric; (b) wild porosities in the waviness area

## 6. Conclusion

Because of their complex architecture, composite materials generally have a limited sensitivity to notches, leading to lower fatigue sensitivity than metallic materials. Nevertheless, in relatively rare case, the analysis of in service failures of composite parts shows that fatigue phenomenon can lead to catastrophic rupture. In almost all these in service failures cases, fatigue damage initiates around manufacturing defects. In the Aeronautical sector, reproducibility of manufacturing processes and performance of NDT reduce the risk of the occurrence of harmful defects. In the coming years, the increasing use of thermoplastic composites for high volume market applications (such as the automotive sector, for example) will make fatigue phenomena around the defects an increasingly important issue. Two main reasons have to be considered: 1- High speed production can generate more defects (especially because the high viscosity of thermoplastic polymers increases the risk of imperfections both in the matrix itself but also in terms of fibers orientations) / 2- Mass production is not compatible with NDT control at 100%.

Understanding in service failure is very instructive as feedback to improve the design of parts and better understanding the critically of defects. For instance, when the main root cause of damage is manufacturing defects, the tolerance criteria of defects are adjusted or specific NDT are added on the control line.

Considering the future, knowledge acquired for about 3 decades on fractography of organic matrix composite materials will have to be completed. The entry of new materials on the market (auto-reinforced polymers, new polymers...) and the development of 3D composites will require to understand their specific damage mechanisms and to identify the corresponding fractographic events (especially in fatigue).

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